A Model of Seasonal Variability in the Indonesian Archipelago

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LONG-TERM GOALS

The ultimate goal is to understand quantitatively factors determining the circulation within and through the Indonesian archipelago on a range of time-scales. This will enable us to evaluate how best to 'parameterize' the archipelago in 3-D numerical ocean circulation models used in forecasting, which cannot resolve the archipelago's thousands of small islands and straits. The theories and models are being developed in a general framework, so that they may have application to arbitrary multiple-strait systems.

OBJECTIVES

This year's objective was to examine the new data from the ARLINDO moorings in the Indonesian archipelago, and interpret them in the context of previously developed models.

APPROACH

The task was not straightforward. The moorings, MAK1 (118^{o} 27'E, 2^{o}52'S in 2137m) and MAK2 (118^{o}38'E, 2^{o}51'S in 1611m), were successfully recovered from Makassar Strait, but the mooring from Lifamatola Strait, in the eastern archipelago, was not recovered after a second attempt in November 1998. Also, the upward-looking ADCPs at 180m on the MAK1/2 moorings flooded when very strong diurnal and semi-diurnal tides blew over the moorings. However, the data recovered from the current meters at 200m, 250m and 350m (zero-wire angle) provided a good sampling of the currents between 250m and 500m, and were gridded at 10m intervals, as described in Gordon & Susanto (1999). Data were also recovered from the current meters at 750m and 1500m (MAK1 only). Gordon et al. (1999) had made estimates of total transport through Makassar Strait for the time period December 1996 to July 1997 using empirical profiles for the upper 250m. As earlier 3-D numerical models had shown that most of the transport occurs above 250m, see e.g. Wajsowicz (1999), I decided to investigate a more objective approach to estimating the currents over the upper 250m. My approach was to use information about the structure of the normal modes in the Strait. If data are available over the whole water column, then the coefficient for each mode is uniquely determined. For the MAK1/2 data, the coefficients can be at best estimated using a least-squares fit, say. As the modes are not independent over the data range, a multivariate fit is not appropriate, and so the modes were fitted in sequence from lowest to highest mode number. This choice was based on knowledge that energy on monthly time-scales is usually concentrated in the lower-order modes, i.e. barotropic, and first and second baroclinic modes. Other fits were considered, as was the effect of the ADCP data, which was available for December 1996 through February 1997 from the MAK2 mooring. Although sophisticated techniques exist for time-series analysis, a simple Fourier decomposition was used to extract information about the mean transport and its seasonal-to-interannual variability.

In order to assess the validity of the reconstructed current profiles, the vertical current structure in a GCM and a quasi-isopycnal, reduced-gravity model were examined. For the latter model, seasonal cycle simulations forced by two different wind-stress products were used. The numerical models were also used to investigate how representative Makassar Strait magnitudes were of the total throughflow into the Indian Ocean.

WORK COMPLETED

Monthly-averaged currents were obtained from the ARLINDO group for the MAK1 and MAK2 moorings. A concurrent temperature data set from the T-pods on the moorings was also obtained. These latter data were gridded at 10m intervals from 150m to 400m. To constrain the least-squares fit further, the current meter data were linearly interpolated between 500m and 1500m. The normal modes for pressure (velocity) and temperature were computed from Levitus (1982) buoyancy frequency profiles in Makassar Strait, see Gill (1982) Ch. 6 for theory on normal modes. Least-squares fits were performed in sequence from lowest to highest mode number, and in reverse order, on the MAK1 data set. For the MAK2 data set, least-squares fits were performed on the current-meter-only data set, and on the current-meter plus ADCP data set. The resulting coefficients were combined with the modes to reconstruct the current profiles over the total depth. A Fourier analysis was made of the resulting total transport to provide upper/lower bounds on the amplitudes for the climatological mean net transport and the seasonal-to-interannual variability; exact values could not be obtained due to aliasing of the natural forcing frequencies between the Fourier harmonics. Fourier analyses with depth were also made on the actual currents and temperatures to assess the modal structure at a given frequency, and to help resolve whether the perturbation energy was locally or remotely generated.

Model output from POCM, the Parallel Ocean Climate Model, run by Prof. Semtner's group at NPGS was obtained for 1987-1995, which did not overlap the MAK1/2 data sets. This was intentional, as the model was not designed to simulate the circulation within and through the archipelago, and so a direct comparison did not make sense. Rather, I wanted to look for features in common between the observational and model data. Output from a second 3-D primitive-equation model, POSEIDON was also investigated. This model is a quasi-isopycnal, reduced-gravity model developed for ENSO simulations by Prof. Schopf, formerly at NASA/GSFC. It has several advantages over POCM in that it has an explicit mixed-layer and high vertical resolution over the upper thermocline, see Wajsowicz & Schopf (2000). Seasonal cycles of the model were obtained for simulations forced by ECMWF and SSM/I-derived wind stresses, as the results were quite different for each.

RESULTS

The climatological buoyancy frequency profiles at locations deeper than 2000m in Makassar Strait are very similar, and yield the pressure and temperature normal modes displayed in Fig. 1. Also shown in Fig. 1 are the depth ranges of the monthly-averaged gridded data from the MAK1 mooring. The seasonal thermocline lies above 150m, therefore the anomalies in the T-pod data are either episodic or interannual. The maximum amplitudes for the pressure modes lie above 200m, therefore the current meter data are unlikely to have captured the bulk of the mean transport or its variability. The results from fitting climatological normal modes in sequence from lowest to highest to the MAK1 data are shown in Fig. 2. The currents between 250m and 1500m are almost indistinguishable from the original data. The reconstructed currents above 250m are southward for all 20 months of the time series, and reach up to 2ms^{-1} at the surface, see Fig. 2a. The resulting transport integrated over the total depth, over the upper 300m, and between 300m and 1500m, are shown in Fig. 2b. The estimates are obtained by assuming the current is uniform across the Strait at a given depth. Therefore, the southward maximum of 24Sv in July 1997 and minimum of 3Sv in October 1997 may be assumed to represent upper bounds, as the equivalent MAK2 currents are typically 10% less than those at the MAK1 site.

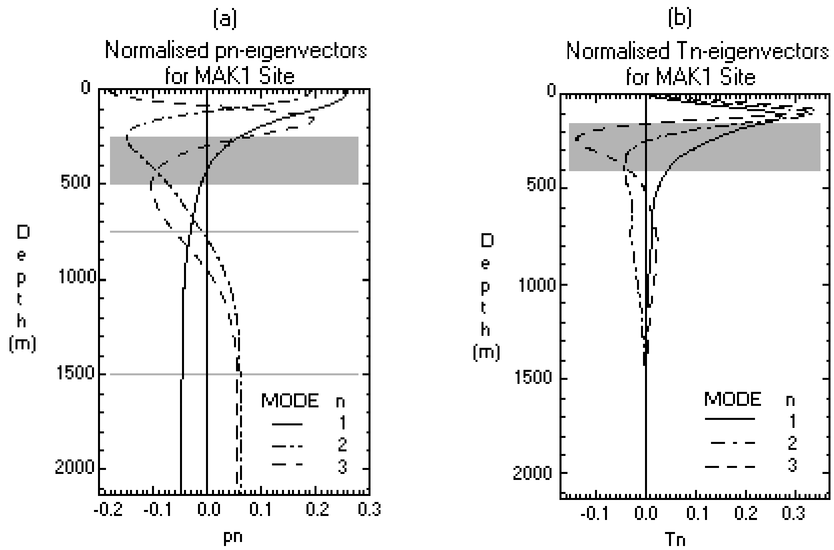

Fig. 1: The normalised pn-eigenvectors for horizontal velocity are plotted in (a) for the first three baroclinic modes. The equivalent wavespeeds are 2.34, 1.18 and 0.80 ms^{-1}. The barotropic wavespeed is 145 ms^{-1}. The depths over which current meter data from the MAK1 mooring have been processed to give monthly averages are shaded light grey. The normalised Tn-eigenvectors for temperature are plotted in (b) for the first three baroclinic modes. The depth range of the gridded T-pod data is shaded light grey.

In this reconstruction, most of the transport occurs over the upper thermocline, as the structure of both the mean and anomalies fields is dominated by the first baroclinic mode. Time series of the coefficients show that the barotropic and first baroclinic mode variability are closely linked, see Fig. 2c. Further, the interannual component of the first mode lags that of the barotropic mode by just under a month, see Fig. 2d, which is consistent with the idea that they have the same source in the western-central equatorial Pacific. In fact, the interannual variation in transport is consistent with the island rule prediction of decreased southward transport through the archipelago in response to the relaxation of the tradewinds at the onset of the 1997/98 El Nino, and enhanced transport during the preceding and ensuing La Ninas. The concurrent T-pod temperature data supports the idea of cold, upwelling, long Rossby waves entering the Strait during an El Nino, and warm, downwelling waves entering during a La Nina. The time series for modes 2 to 4 are in phase with the barotropic component, which suggests that they are generated within the archipelago, most likely as a Rossby adjustment to the 600m-800m sills at the southern end of Makassar basin.

A Fourier decomposition of the transport time series in Fig.2b showed the semi-annual component dominated the annual component, upper bounds on their amplitudes are 4.3Sv and 2.7Sv respectively, and that there was a similar amount of energy in motions with 4-5 month timescales. The result is surprising, as it was known from Murray & Arief (1988) that Lombok Strait to the south had a significant semi-annual signal, but GCMs have always given a dominant annual period signal. Re-examining Meyers et al.'s (1995) calculations on inferred geostrophic throughflow transport relative to 400m from XBT data revealed a dominant semi-annual signal as well. The amplitude of the interannual signal is estimated to lie between 3.6Sv and 5.6Sv, and the climatological mean is at least 11Sv.

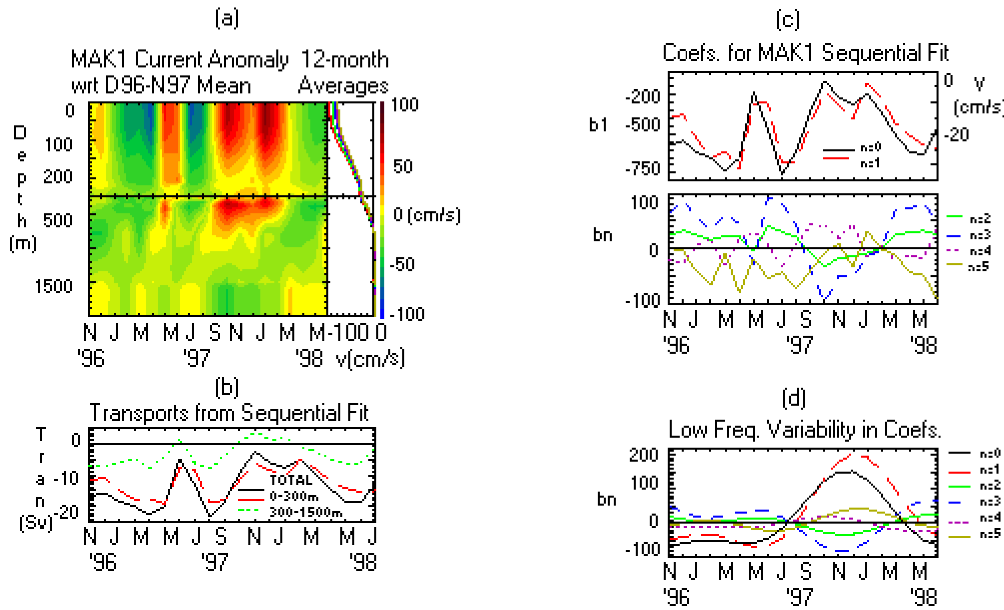

Fig. 2: Normal modes are fitted to the MAK1 current meter data using a least-squares method with each baroclinic mode fitted in sequence starting with the first. Using this method, the barotropic velocity is given by the residual constant. The reconstructed current anomaly is contoured as a function of time and depth on the lhs of (a), and 12-month means for the 20-month series are plotted on the lhs of (a). The inferred net transport over a range of depths, assuming the velocity profile in (a) holds across the width of the Strait, are plotted in (b) as a function of time. The temporal variability of the mode coefficients are plotted in (c), and their low-frequency variability (<1/(10 months)) in (d)

A second reconstruction in which the normal modes were fitted in reverse sequence yielded weak currents over the upper 250m with unrealistic shears. The net transport over the upper 300m was less than 3Sv, and had almost no variability at any frequency. Hence the net transport over the total depth had similar variability to the previous reconstruction, but its mean was smaller. A reconstruction from lowest to highest mode for the three months for which ADCP data were recovered from the eastern mooring, MAK2, showed that the fit considerably overestimated the contribution of the first baroclinic mode, see Fig. 3. Including the ADCP data led to a reduction in upper thermocline transport of 50%, but the total net transport was almost unchanged.

The 3-D numerical simulations showed a remarkable array of contrasting temporal behavior and vertical structure in the upper 250m of Makassar Strait. They suggest that the two reconstructions provide upper and lower limits on the net transport, both its mean and variability. The numerical models also showed that on interannual time-scales, the transport and temperature variability in Makassar Strait should contain the majority of the throughflow signal. However in POCM, the 1987/88 El Nino and subsequent La Nina signals from the Pacific passed through the Banda Sea rather than Makassar Strait. Whether this was an artefact of the spin-up of the model, or a real possibility is the subject of further investigation. On seasonal time-scales, the numerical models showed that the net throughflow variability could only be explained by adding the Makassar Strait and Banda Sea signals. Further, if considering the flow over the upper thermocline, then there was sufficient upwelling/downwelling in the southern seas of the archipelago, that there was little relationship between Makassar Strait transport and flow from the archipelago into the Indian Ocean on seasonal time-scales. This research has been submitted for publication in JPO, Wajsowicz et al. (2000).

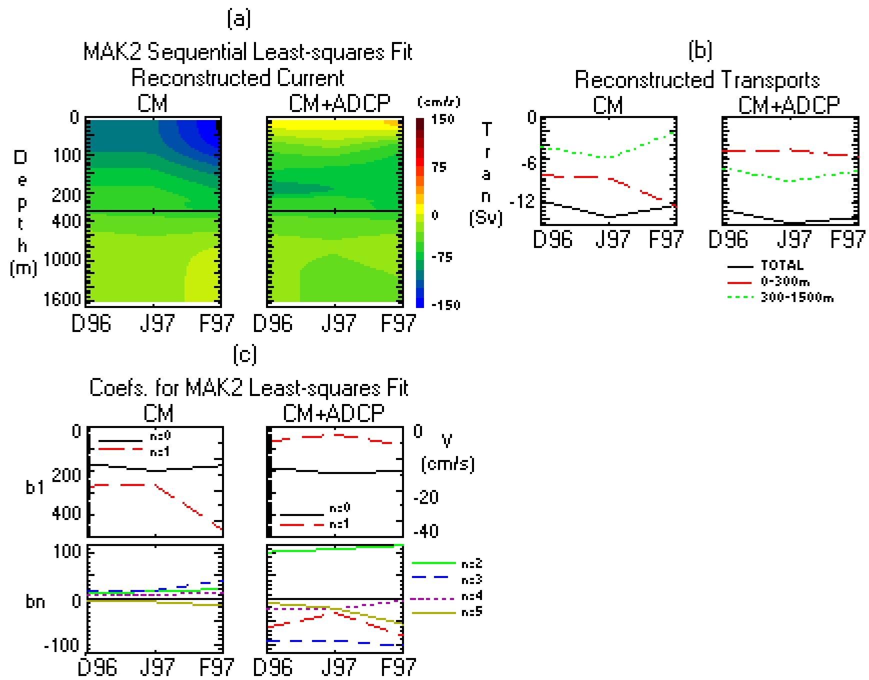

Fig. 3: A comparison of a least-squares fit of all normal modes in order from lowest to highest for the MAK2 current meter data only on lhs, and current meter plus ADCP data on rhs. The reconstructed current profiles are shown in (a). The inferred net transport over a range of depths are plotted in (b). The baroclinic mode coefficients from the fit are plotted in (c).

IMPACT/APPLICATIONS

The development of sophisticated, numerical models for forecasting the ocean circulation and hydrographic state is a high priority for ONR, as is knowledge and understanding of the ocean circulation in strategically important regions such as the Indonesian archipelago, other East Asian marginal seas, and the Caribbean.

TRANSITIONS

In general terms, my ONR-funded research provides a theoretical framework to support ONR's field programs in the region (Gordon's ARLINDO and Sprintall's network of shallow pressure gauges in the exit straits), and the numerical primitive-equation modeling research at NRL, Mississippi (Hurlburt, Kindle and Preller) and NPGS (Semtner, Tokmakian and McClean). Also, the generality of the theories developed means that they have application to other multiple strait systems. I have approached the Intra-Americas Seas Initiative to investigate application of my theories to the Caribbean, and shall present my research at their conference in Panama in November 1999.

RELATED PROJECTS

I am also funded by NASA to investigate the hydrological cycle in the Indo-Pacific region, which involves running high-resolution, global numerical ocean models. Accurate simulation of the transport of heat and fresh-water fluxes between the Pacific and Indian Oceans is crucial for these investigations.

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